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A Study On Fatigue Analysis of Offshore Tubular Joints

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해양 구조물 튜불러 죠인트의 피로 해석에 대한 연구

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Abstract

In this paper, typical tubular joints' fatigue strength is investigated focussing on the Stress Concentration Factors calculation using Finite Element Methods. For the calculation of the SCF of the members, the joints are modeled using thin shell elements and comprehensive analysis are carried out. Related techniques for the numerical analysis are studied. Experimental studies are performed for the verification and comparison with the numerical analysis results. Model tests of K joints are carried out not only for finding SCF values but also for the calculation of fatigue lives of the joints using specially designed test facilities.

요 약

본 논문에서는 전형적인 해양 구조물의 튜불러 죠인트 피로강도에 대해서, 유한 요소법을 이용한 응력집중 계수 산출과 피로수명에 대한 영향에 관점을 맞추어 고찰하였다. 이를 위하여 죠인트를 박판 쉘 요소로 모델링 하였으며 총체적인 해석을 수행하였고 수치해석을 위한 기법에 대해 연구하였다.

수치해석 결과에 대한 비교와 검증을 위해 실험적 연구를 수행하였으며 특히 응력집중계수 산정 및 피로수명을 산정하기 위하여 K죠인트에 대한 실 모델 테스트를 특별히 고안된 실험 시설을 이용하여 수행하였다.

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1. Introduction

In 1965 an early example of fatigue damage occurred in a triangular semi-submersible drilling rig in the Gulf of Mexico. From that time on, various kinds of fatigue failures of ocean structrues have been reported. As a result, the importance of fatigue life estimation at the design stage was recognized and various kinds of analysis approaches have been discussed[1]. Fatigue crack growth results from predominantly dynamic loading, relatively high local stresses, application of high strength steel and fabrication defects. For offshore structures subject to variable loads such as wave loads, a probabilistic approach using spectral analysis methods is preferable. Spectral analysis is a technique capable of relating, in a statistical manner, cause and effects due to randomly occurring phenomena[2].

In this paper characteristics of the spectral method are studied and the elements of the approach are discussed. The concepts of maximum stress concentrations phenomenon at certain points which are commonly referred to as hot spots and the stresses at these locations "hot spots stresses" are discussed. Various kinds of stress concentration factors formula and the application of FEM for searching for SCFs are studied. Generally, FEM analysis is necessary for complex joints to which known SCF formulas cannot be applied. On the other hand, for simple T, K, joints and similar ones, formulas such as Gibestein's, Kuang's, Wordsworth's, Smedley's, Kinra's and Efthymiou's are applicable depending on the characteristics of the joints considered[3, 4].

In the following, components of the spectral fatigue analysis are reviewed and the roles and the characteristics of SCF in the fatigue problems are studied in the view point of numerical and experimental analysis. Comparison of SCF values of typical K joint obtained by different methods are carried out. Also fatigue tests are performed for the joints.

2. Spectral Fatigue Analysis

Metal fatigue in welded structures is a complex phenomenon affected by a number of synergistic factors, the most important being the cyclic stress range[5]. For most offshore structures, a spectral fatigue analysis approach, may be performed without any difficulties. In this case, wherein the entire long-term distribution of fatigue stresses is determined in each specific case, considering the characteristics, such as significant wave height and representative wave period, of each sea state and the time spent in it[6, 7].

The spectral method applies the theory of stochastic processes for the calculation of the response to environmental loading, especially wave loading. For a particular sea state, spectrum of a response variable is found by combining wave spectrum of response. By integrating wave amplitude to amplitude of response. By integrating the response spectrum, variance of response and spectral moments can be calculated. Once the stress spectrum for a particular point in the structure during a certain sea state is known, predictions of the stresses experienced at that location can be made. All statistical stress predictions are related to the moments of the relevant stress spectrum about the origin. Spectral fatigue analysis procedures are well introduced[2, 7].

Among the major elements of the fatigue

analysis, for example, environmental condition, stress concentration factor, S－N curve, the crucial element is found to be the stress concentration factor. Typical sensitivity analysis shows that a doubled SCF increases damage ratio by 21 times [6]. SCF may be said to be the most sensitive factor in fatigue behavior of offshore structures.

3. Stress Concentration Factors

Stress concentration can be defined as a condition in which a stress distribution has high localized stresses: usually induced by an abrupt change in the shape of a member ; in the vicinity of notches, holes, changes in diameter of a shaft, and so on, maximum stress is several times greater than where there is no geometrical discontinuity. The stress concentration factor is the ratio of the greatest stress in the region of stress concentration to the corresponding nominal stress.

The SCF may be calculated from theory of elasticity by various methods. Analytical methods tend to become mathematically complicated, and are applicable to simple geometries only. Finite Element Method is more versatile. For 3-dimensional case, the Finite Element Method is still practical, but is very expensive in many cases. The SCF may be estimated based on parametric equations or experimental data. Finite Element Method is used commonly to determine the stress distribution and hot spot stress especially for complex tubular joints. Shell elements traditionally have been used for the SCF calculation. However it is difficult to include the geometry in the weld region in the FEM modeling. Stress analysis by FEM is the most efficient, reliable and economical tool for datailed stress analysis of tubular joint with the rapid development of computation skills and modeling techniques and high speed computers.

There are many formulas for SCF calculation which were obtained by numerical analysis or experiment. Several researchers have suggested empirical approximations for SCFs in tubular joints[3]. Generally, nondimensional ratios of geometric parmeters are used to allow for the generalization of the results to many joint sizes.

SCF is assumed as a function of parameter γ, β, τ, ζ, θ, as:

$$SCF = f_1(\gamma)\cdot f_2(\beta)\cdot f_3(\tau)\cdot f_4(\zeta)\cdot f_5(\theta) \qquad (1)$$

γ = D/2T chord diameter to thickness ratio
β = d/D brace diameter to chord diameter ratio
τ = t/T brace thickness to chord thickness ratio
ζ = g/D gap to chord diameter ratio
θ = brace angle with the chord

With the above assumptions for SCF, the actual curve fit of the SCFs was performed in a graphical manner generally. The empirical equation in the form shown below is obtained.

$$SCF = a\cdot\gamma^{m1}\,\beta^{m2}\,\tau^{m3}\,\zeta^{m4}\,\sin^{m5}\theta \qquad (2)$$

Obviously any set of empirical guidelines must be restrained within certain limitations to minimize data dispersion and maintain design applicability. Recent researches on the SCF formulas are performed mostly by making use of numerical analysis[8, 9].

4. Numerical Approach for Fatigue Analysis

SCF calculation of K joint by FEM

The stress analysis using the FEM is performed on the typical K joint models. The geometrical particulars of the models are shown in Table 1.

In the analysis, the axial load of 5 ton was imposed on the brace. To provide a satisfactory

Table 1 Dimension of K joint models

unit: mm

	D	T	L	d	t	g
Model I	168.0	7.1	1400.0	76.0	5.2	45.76
Model II	168.0	10.0	1400.0	76.0	5.2	45.76

model for a tubular joint FEM analysis, the mesh generation was prepared as follows.

(1) 3-D thin shell element was used.

(2) In the immediate vicinity of the branch-to-chord junctions, the dimension of the element was chosen not to exceed $0.75\sqrt{Rt}$ as UKOSRP(United Kingdom Offshore Steels Research Project) recommended. Where R is the radius of the corresponding member and t is the thickness of the member.

(3) Element aspect ratio was chosen not to deviate from unity.

(4) Mesh generation is made to provide that the location of the strain gauge attachment point and the nodal point of FEM analysis are to be coincided. Total number of element is 1,256 and total number of nodal point is 1,266. Fig. 1 and Fig. 2 show the FEM modeling of the K joint.

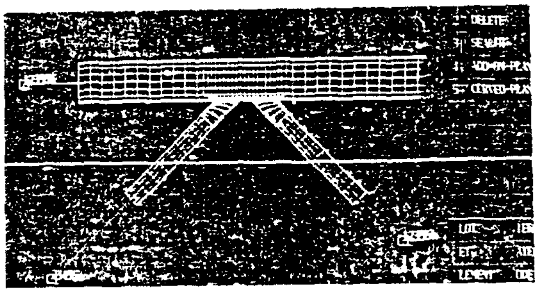

Fig. 1 FEM model of K joint, front view

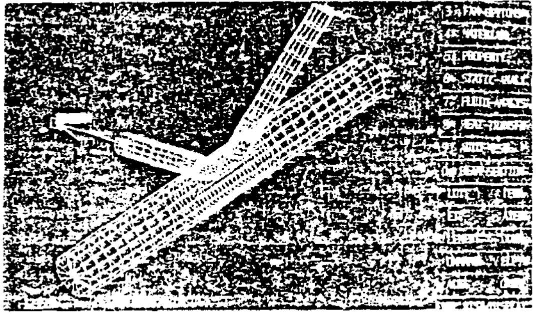

Fig. 2 FEM model of K joint, prospective view

Fig. 3 and Fig. 4 show the mesh configuration and mesh size of joint intersection area of the model.

The boundary conditions of the model for FEM analysis is same as those of the model for actual test. Axial load of 5ton is applied at one brace member with other brace member supported by pin-joint. The chord is in simply supported-free condition. The stress analyses have been carried out on two types of tubular K joints by using the general purpose code for structural analysis NISA II[10]. Fig. 5 and Fig. 6 show the principal stress and the von-Mises stress distribution with hot spot locations, respectively, for model 1.

Fig. 7 and Fig. 8 show the principal stress and the von-Mises stress distribution with hot spot locations respectively, for model 2. Since high local stresses are observed along the intersection lines especially at the saddle point it

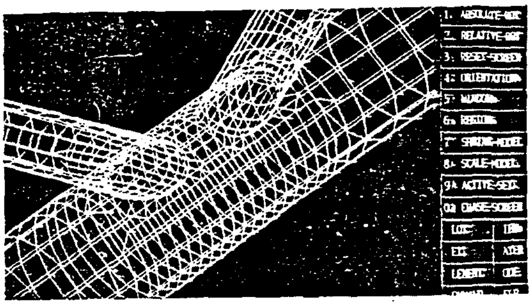

Fig. 3 Mesh configuration at joint intersection

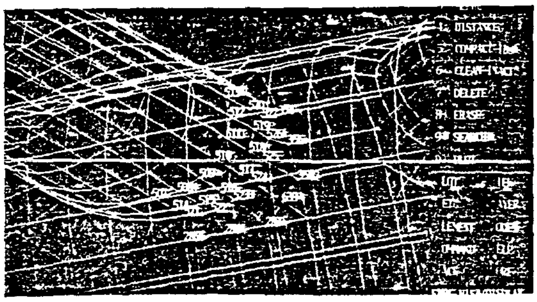

Fig. 4 Mesh size at brace-chord intersection

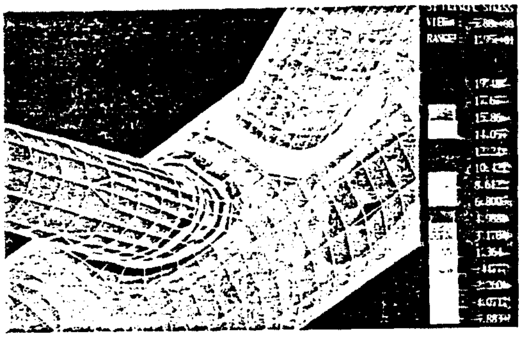

Fig. 5 Principal stress distribution at the intersection for model 1

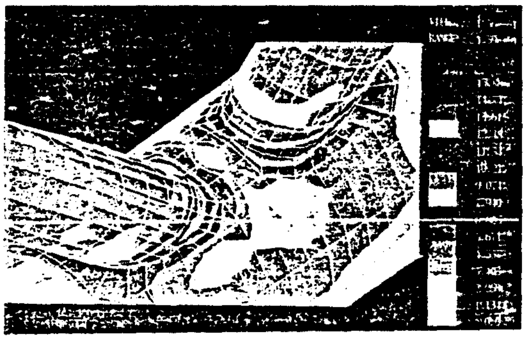

Fig. 6 Von-Mises stress distribution at the intersection for model 1

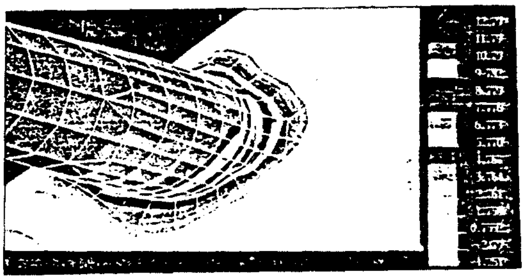

Fig. 7 Principal stress distribution at the intersection for model 2

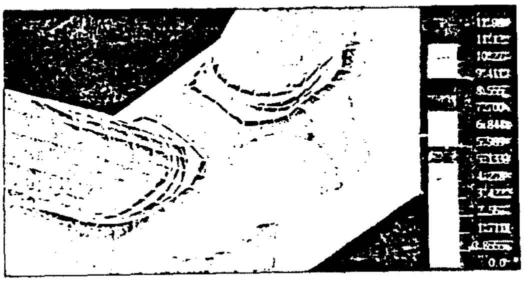

Fig. 8 Von-Mises stress distribution at the intersection for model 2

Table 2 SCF values obtained by FEM

		Chord	Brace	Kuang's formule
Model 1	SCF	4.339	4.213	4.782 (Chord)
	Prin. Stress	18,744	18,200	
Model 2	SCE	2.211	3.229	3.264 (Brace)
	Prin. Stress	9,522	13,949	

may be said that the saddle point area is the most possible failure occurrence area even though there are no welding defects.

Table 2 shows the results of the stress analysis for model 1 and model 2. The location of maximum SCF for model 2 is the center between saddle point and crown point. The location of maximum SCF for model 2 is around the saddle point at brace side.

Fatigue life estimation based on S−N curve

Miner's Rule is most conveniently applied for the fatigue life estimation. The validity of Miner's Rule for random loading conditions is open to question. However, it is known that a linear accumulation of damage is approximately true in cases where fatigue is predominantly a result of the propagation of initial cracks that are already present[2].

For the simple calculation of fatigue life of the K joint using the SCF value obtained previously, American Welding Society curve fr category X is used[1]. There are many S−N curves in existence and they differ greatly, depending on the type of structural detail referred to and the origin of the data. The modified AWS−X curve is used here, since this curve is thought to be most suitable for the case. Using the obtained SCF value of 4.213 for model 1 and 3.229 for model 2 and given axial load of ± 7.5 tons, fatigue life is obtained. The fatigue failure cycle obtained is 11604 for the case of model 1 and 22073 for the case of model 2. These values are thought to be very conservative.

5. Experimental Approach for Fatigue Analysis

SCF calculation of K joint by test.

The SCFs of the specimens which have same dimensions as the models for FEM analysis were estimated using strain gauges readings. The extrapolation techniques have been used to interpret the measured results. Test arrangement for K joint is shown in Fig. 9. A typical strain gauge layout is shown in Fig. 10. To measure the values of SCF, strain gauges were attached at the crown and saddle points of both chord and brace side. To get the stress at the weld toe, the linear extrapolation method of maximum principal stresses is employed. Fig. 11 shows the way of extrapolation of hot spot stress. Table 3 shows the results obtained by the tests.

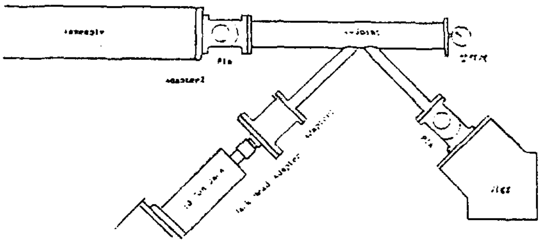

Fig. 9 Fatigue test arrangement

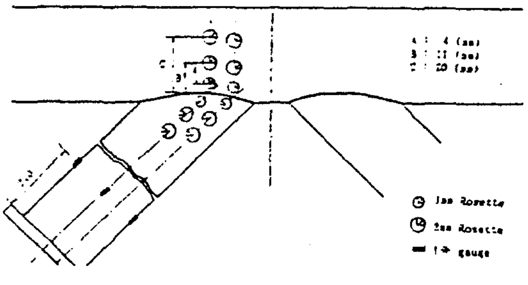

Fig. 10 Typical strain gauge layout

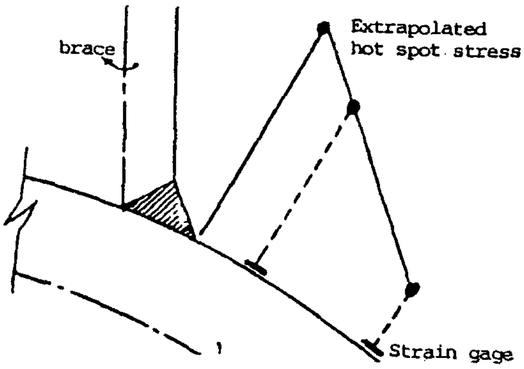

Fig. 11 Extrapolation of hot spot stress

Table 3 SCF values obtained by tests and FEM

		Chord	Brace
Model 1	Test	3.780	3.140
	FEM	4.339	4.213
Model 2	Test	2.500	2.840
	FEM	2.211	3.229

Fatigue test of K−joint

Fatigue tests were conducted on large scale size specimens. The geometrical particulars of the specimen are same as the model used in FEM analysis. Testing layout is shown in the Fig. 9.

Fatigue tests were carried out under load controlled conditions. The chord ends were simply supported and free and the axial load of ± 7.5 ton was applied at the end of the brace. The life of thorough thickness cracking was detected with the aid of pressure gauge which is installed at the end of the chord as shown in the Fig. 9. The results of the tests under the cyclic loading for Model 1 and Model 2 are summarized in Table 4 with the comparison of the results by S−N curve approach. The testing set up is shown in Photo 1. The failure modes of the specimen for model 1 and model 2 are shown in Photo 2 and Photo 3, respectively.

Table 4 Fatigue life by various methods

unit : cycle

	AWS-X Curve	Fatigue test
Model 1	11,604	306,000
Model 2	22,073	515,300

Photo 1 Testing set up

Photo 2 Failure mode for model 1

Photo 3 Failure mode for model 2

6. Discussions and Conclusions

A fully satisfactory solution of fatigue problem has not been achieved yet. Several kinds of approaches are sought. Among these methods, spectral method described here represents physical characteristics more realistically. In the method, stress concentration factor is the most crucial factor in fatigue life calculation. In order to obtain accurate fatigue life calculations, a reasonable estimation of SCF is essential, FEM analysis is necessary for finding SCFs for complex offshore structure joint. Even though the SCF formulas are available, the detailed FEM analysis is strongly recommended. In this paper the SCF values of K joints are obtained by FEM and compared with those obtained by the tests. The values are in good agreement each other in this case.

The experimental approach may be utilized for SCF calculations. The inherent difficulties of experimental approach are exposed. Any set of empirical guidelines must be restrained within certain limitations to minimize data dispersion and maintain design applicability. Recent researches on the SCF formulas are performed mostly by making use of numerical analysis, mainly because of huge amount of time and expenses required for experimental investigation.

Fatigue life estimation based on the spectral analysis may be very conservative. In this paper, fatigue life of the K joint obatined by the spectral method is come out to be more than 30 times conservative comparing with the actual test results. However, the spectral method, with the realistic SCF values obtained by FEM is thought to be main tool for solving the problems.

The main conclusions drawn from the study are as follows:

(1) The integrity of offshore structure is critically dependent on the behavior of tubular welded joints which are subjected to stress concentration and thus fatigue. Despite of all the progress made for the solving of stress concen-

tration problems, FEM is the reliable main tool for solving the problems.

(2) To provide a satisfactory model for a tubular joint stress analysis, thus for precise SCF value calculations, mesh generations need to be carried out carefully according to the geometry of the member, boundary conditions and loading circumstances.

(3) Spectral fatigue analysis gives very conservative results. However the method is by far the most convenient and economical tool for the estimation of the fatigue life of offshore structures.

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